REVISED ESTIMATES FOR SCR-PRODUCED ^{22}NA IN LUNAR ROCK 74275 USING NEW CROSS SECTION MEASUREMENTS.

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Radionuclides are produced in lunar rocks by the interactions of both solar and galactic cosmic rays. The different properties of solar cosmic rays (SCR) and galactic cosmic rays (GCR) allow the measured activity-depth profiles to be analyzed to give information about the solar proton flux over a time period characterized by the cosmogenic nuclide under study and the sample's exposure history [1].

GCR particles are ~87% protons, can have very high energies and penetrate to great depths in the lunar surface, but the flux is low. Many secondary neutrons are produced in their interactions with the lunar material.

~98% of SCR particles are protons, with most having energies <100 MeV, and penetrate only the top 1-2 cm of the lunar surface. Usually the flux of solar protons is very low, near zero. At rare times of high solar activity, such as July 1959, Nov. 1960, Aug. 1972, and Oct. 1989, the solar proton flux can be very high, with event-integrated fluences of ~10^{10} protons/cm^2 above 10 MeV over a period of only a few days [2,3].

The theoretical models used to analyze the cosmogenic nuclide archive require as input the cross sections for the interactions of all cosmic ray particles with all constituents of a lunar rock. Most SCR reactions are proton interactions that produce very few secondary neutrons so, to study solar proton effects, good cross sections for incident protons are essential. To study GCR effects, or to make good GCR corrections to the SCR data, cross sections for protons with energies >200 MeV are needed as well as cross sections for incident neutrons.

One model often used to calculate the solar proton flux is the Reedy and Arnold (1972) [4] model. At that time, few of the needed cross sections had been measured, so estimated values were used in the calculations. Recently, many cross sections [e.g., 5-7] have been measured, and now much better estimates of the solar proton flux over the time periods characterized by many cosmogenic radionuclides can be made [8].

Relatively short-lived radionuclides have been measured in some lunar rocks, and, in 1982, Fruchter et al. reported the activity-depth profile for ^{22}Na ($T_{1/2}$ = 2.6 years) in lunar rock 74275 using non-destructive counting techniques [9]. This lunar rock has a chemical composition of O = 41.3%, Si = 18%, Fe = 14%, Ca = 7.3%, Ti = 7.65%, Mg = 6.3%, and Al = 4.73% [10]. The measured activity depth profile was compared to a theoretical profile calculated using the model and the cross section data sets of Reedy and Arnold [4]. The solar-proton flux for the August 1972 event was inferred by [9] to have a spectral shape of R_o = 150 MV and an effective 4π flux >10 MeV of 130 p/cm^2 s. GCR corrections were made using information available at that time.

New cross section data set compilations have been made for Si(p,x)^{22}Na [8], Mg(p,x)^{22}Na, Al(p,x)^{22}Na, Ca(p,x)^{22}Na, Ti(p,x)^{22}Na and Fe(p,x)^{22}Na incorporating recent measurements [e.g., 5-7]. Reactions with Mg, Si, Al and Na account for >99% of the ^{22}Na production in 74275 with the reaction off Mg accounting for >50%.

Figures 1 and 2 show the cross section data sets for Mg(p,x)^{22}Na and Al(p,x)^{22}Na including the cross section data sets used in the 1982 calculations of [9] (Re72), in our study [8] of SCR-produced ^{22}Na in lunar rock 12002 (S5P), and for this work (S6P).

The cross sections shown in Figs 1 and 2 illustrate that the new cross section data sets (S6P) can be used with confidence because there is good agreement in the cross section values measured independently by different groups.

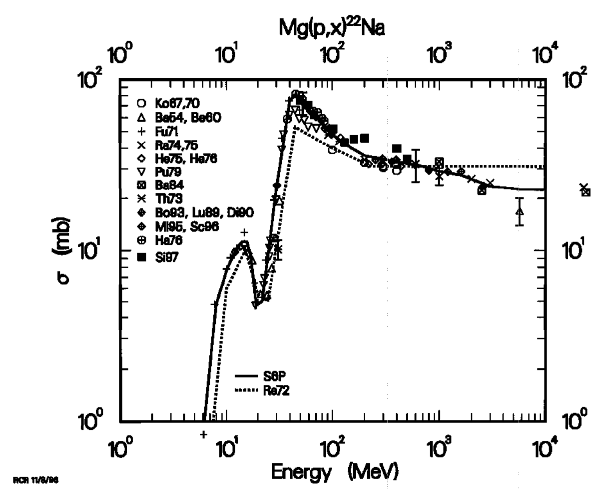

Fig. 1. Mg(p,x)^{22}Na measured cross sections and adopted cross-section sets.

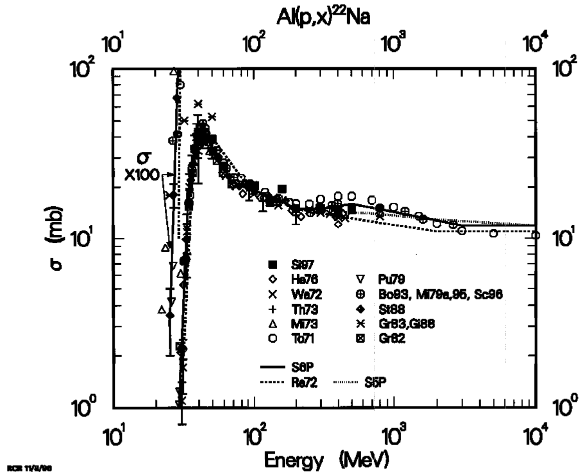

Fig. 2. Al(p,x)^{22}Na measured cross sections and adopted cross-section sets.

Most of the ^{22}Na activity induced in 74275 was as a result of the large solar proton event (SPE) of August 1972. To get the contribution for only the August 1972 SPE, the measured ^{22}Na activities in 74275 need to be corrected for production by all SPEs except that in August 1972 and for GCR production. After these corrections, which are more important for the deeper samples than for the surface ones, one can calculate the solar proton spectral shape and effective flux for the August 1972 SPE, which can then be compared to those measured directly by satellite.

The proton flux effective for ^{22}Na for SPEs except August 1972 since 1956 up to December 1972 was determined from event-integrated fluences [2] to have a spectral shape of R_o=55 MV and a 4π flux above 10 MeV of 70 p/cm^2 s.

The production of ^{22}Na at depth in several lunar rocks indicate that the GCR production rates calculated with the model of [4] are too high and should be reduced by a factor of ~0.7.

For 74275, reducing the GCR contribution to the measured data calculated using the Reedy and Arnold model [4] by 0.7 and including the correction for other SPEs, theoretical estimates using the S6P data set for various solar proton spectral parameters were fitted to the corrected measured ^{22}Na activity data.

The best fit was obtained for R_0=130 MV and an effective 4π flux above 10 MeV of 160 p/cm^{2}s for the August 1972 SPE, which should be compared to the satellite measured spectral shape of R_0=90-100 MV and an effective flux (for ^{22}Na) of 172 p/cm^2 s 4π for E>10 MeV [2]. There is good agreement in the flux values, but the lunar rock 74275 data for ^{22}Na indicates a harder spectrum for this SPE.

The best fit with the Re72 data set was R_0=120 MV and a flux of 226 p/cm^2 s 4π for E>10 MeV. The main difference between these two sets is that the old set (Re72) gives production rates that are ~15-20% lower than does S6P for lunar samples with this composition.

More work is required to understand and explain this discrepancy between direct measurements by satellite of the solar proton spectra and fluxes and those estimated from the cosmogenic radionuclide archive. The GCR correction especially needs to be better determined for samples of various compositions.

Until recently, however, disagreements of this type could not be explored in detail because there was always a question about the accuracy of the cross section data used as input to the theoretical calculations. Now that we have cross section data sets that can be used with confidence, it is possible to refine our understanding of the solar proton flux both in the past and present. Doing so will allow better estimates of the radiation hazards that might be encountered in space due to energetic solar particles.

REFERENCES. [1.] Reedy R.C. and Marti K., (1991), in *The Sun in Time* (The University of Arizona Press), 260-287. [2.] Reedy R.C., (1977), *Proc. Lunar Sci. Conf. 8th*, 825-839. [3.] Shea M.A. and Smart D.F., (1992), *Radiocarbon 34*, 255-262. [4.] Reedy R.C. and Arnold J.R. (1972), *J. Geophys. Res.* 77, 537-555. [5.] Sisterson J.M. *et al.*, (1997) *Proc. Conf. Applications of Accelerators in Research and Industry*, Denton, TX, Nov 1996 (in press). [6.] Sisterson J.M. *et al.*, (1996) *Nucl. Instr. Meth. Phys. Res.*, (in press). [7.] Schiekel Th. *et al.*, (1996), *Nucl. Instr. Meth. Phys. Res.*, *B114*, 91-119. [8.] Sisterson J.M. *et al.*, (1996), *Lunar Planet. Sci. XXVII*, 1209-1210. [9.] Fruchter J.S. *et al.*, (1982), *Lunar Planet. Sci. XXIII*, 243-244. [10.] Rose H.J. *et al.* (1975), *Proc. Lunar Sci. Conf. 6th*, 1363-1373.

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